Problems in Microgravity Fluid Mechanics: G-Jitter Convection

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Final Report

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This is the final report on our NASA grant, "Problems in Microgravity Fluid Mechanics" NAG3-2513: 12/14/2000 - 11/30/2003, extended through 11/30/2004. This grant was made to Stanford University and then transferred to the University of California at Santa Barbara when the PI relocated there in January 2001. Our main activity has been to conduct both experimental and theoretical studies of instabilities in fluids that are relevant to the microgravity environment, i.e. those that do not involve the action of buoyancy due to a steady gravitational field. Full details of the work accomplished under this grant are given below. Our work has focused on:

(i) Theoretical and computational studies of the effect of g-jitter on instabilities of convective states where the convection is driven by forces other than buoyancy

(ii) Experimental studies of instabilities during displacements of miscible fluid pairs in tubes, with a focus on the degree to which these mimic those found in immiscible fluids.

(iii) Theoretical and experimental studies of the effect of time dependent electrohydrodynamic forces on chaotic advection in drops immersed in a second dielectric liquid.

Our objectives are to acquire insight and understanding into microgravity fluid mechanics problems that bear on either fundamental issues or applications in fluid physics. We are interested in the response of fluids to either a fluctuating acceleration environment or to forces other than gravity that cause fluid mixing and convection. We have been active in several general areas.

g-jitter: Our g-jitter work has been focused on linear and nonlinear analyses and simulations of the effect of transient accelerations on fluid flows. We have studied both the case when there is a large, mean gravity, (Christov & Homsy, 2001), as in a vertically stratified cavity, and when there is not: Suresh & Homsy (2001), as in flows driven by thermocapillary stresses rather than mean buoyancy. In the both cases, we are interested in the possibility of resonant interactions between the instability modes of the unmodulated flow, and on parametric instabilities that are intrinsically associated with the modulation itself. These studies establish the stability limits for such flows, and characterize the nonlinear states that replace the simpler ones above the critical conditions for instability. Our current approach to these problems is primarily theoretical and/or computational. Time-dependent parallel flow solutions for temperature and velocity are determined and the resulting linearized equations for perturbations are solved by a combination of numerics and Floquet theory.

Chaotic mixing: Our theoretical analysis, Ward & Homsy (2001) indicates that it should be possible to mix drops very effectively using modulated electric fields. The velocity and stress fields can be obtained in the quasistatic limit by analytical approaches, since the flows in question are Stokes flows. The resulting advection equations for the position of Lagrangian fluid elements are integrated as initial value problems to determine regions of chaotic mixing, Lyapunov exponents, Poincare maps, etc. We designed and built an apparatus for experimental verification of the theory which was also published in Physics of Fluids: Ward & Homsy (2003). We have also completed a combined theoretical/experimental study of chaotic mixing in steady three-dimensional electrohydrodynamic flows. Predictions indicate that even steady flows will mix effectively if there is an angle between the vorticity vectors due to migration and electrohydrodynamic stresses. We have recently modified our experimental apparatus, adding the ability to track particles stereo-optically, to test our theoretical predictions. A paper submitted to J. Fluid Mechanics is soon to be accepted there: Ward & Homsy (2005).

Electro-osmotic flow: Instabilities in electro-osmotic flow open the possibility of other mechanisms of mixing. We have analyzed the instability of AC electro-osmosic flows in microchannels and microdevices. Electro-osmotic flows in the presence of AC fields again leads to time-dependent parallel solutions for the flow and ion concentration fields. This work is theoretical in nature, and is closely related in its mathematical content to our earlier work on g-jitter convection. Our theoretical studies have indicated that the stability of AC electro-osmotic flows can be decomposed into two separate problems: an equivalent Stokes layer problem, and an electroconvection problem for ion transport. Theory indicates that both sub-problems are linearly stable, indicating that the observed instabilities might be due to either other mechanisms or to finite amplitude effects. This work has been published in Suresh & Homsy (2004).

Mixing in miscible flows. Our work on instabilities in miscible displacement was motivated by NASA's general interest in miscible flow phenomena, and in the proposed experiment by Tony Maxworthy, Eckart Meiburg, and their colleagues. We have recently published some experiments in which we made a careful study of a newly-discovered instability during displacement of two miscible fluids in tubes, Scoffoni, et. al. (2001).

Publications acknowledging NASA support

Christov, C. & G. M. Homsy, "Nonlinear Dynamics of Two-Dimensional Convection in a Vertically Stratified Slot with and without Gravity Modulation", J. Fluid Mech. **430**, 335, 2001.

Scoffoni, J., E. Lajeunesse, & G. M. Homsy, "Interface Instabilities during Displacements of Two Miscible Fluids in a Vertical Pipe", Phys. Fluids **13**, 553, 2001.

Suresh, V. & G. M. Homsy, "Stability of Return Thermocapillary Flows under Gravity Modulation", Phys. Fluids **13**, 3155, 2001.

Ward, T. & G. M. Homsy, "Electric Field Induced Chaotic Advection in a Translating Drop", Phys. Fluids. **13**, 3521, 2001.

Suresh, V. " Stability of Flows Subject to Time-Dependent Body Forces", PhD Thesis, Dept. Chemical Engineering, Stanford University, 2001.

Suresh, V. & G.M. Homsy "Stability of Time-Modulated Electroosmotic Flow, Phys. Fluids, **16**, 2349 (2004).

Ward, T. & G. M. Homsy, "Electrohydrodynamically driven chaotic mixing in a translating drop. Part II. Experiments", Phys. Fluids **15**, 2987 (2003).

Ward, T. & G. M. Homsy, "Chaotic streamlines in a translating drop with a uniform electric field", to appear in J. Fluid Mech. (2005).

Degrees granted, number of students supported

Vinod Suresh, PhD student, received his degree from Stanford University in Summer, 2001. He is now a postdoctoral fellow in the Dept. of Biomedical Engineering, Univ. Michigan.

Kausiksankar Das, Postdoctoral Fellow, joined the group in July, 2001. He is currently at the Univ. of Strathclyde, Glasgow, Scotland.

Thomas Ward, PhD student, UCSB, received his degree from UCSB in Fall, 2004. He is currently a postdoctoral fellow at Harvard University.